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# Does too much work hamper innovation? Evidence for diminishing returns of work hours for patent grants

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# Does Too Much Work Hamper Innovation? Evidence for Diminishing Returns of Work Hours for Patent Grants

Mehmet Güney Celbiş* Serdar Türkeli*

September 8, 2014

**Abstract**

This study suggests that individual time is an important factor that needs to be considered in innovation research. We define two types of time: work time and free time. We find that work time has a positive but diminishing effect on innovative output such that after a certain point the innovation-enhancing role of work time is taken over by individual free time. Using a sample of OECD countries and Russia covering the period 2000-2011, we estimate a quadratic relationship between work time and per capita innovative output. For a hypothetical economy that has no other holidays but weekends, we estimate that individuals should not work more than about 6.6 hours a day for maximizing innovative output. We also present a categorization of countries based on their innovative output and work hours that may kindle interest for certain case-specific future research.

**Key words**: Innovation, Patents, Working Hours, Time, Neo-Capital Theories, Network Failures

**JEL Classifications**: O30, O31, J08, J22, M5.

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# 1 Introduction

As narrated by Vitruvius, 2,200 years ago[1] Archimedes had spent a long time trying to figure out a definitive answer to clear the suspicion of King Hieron II of Syracuse that whether a jeweler substituted some of the gold to be used in his crown for a cheaper metal like silver. The answer came to Archimedes in a bath while observing water displacement and he immediately hopped out and ran onto the streets naked shouting 'Eureka! Eureka!'.

Many centuries later, a close friend of Sir Isaac Newton, an antiquarian called William Stukeley, recalls: "after dinner, the weather being warm, we went into the garden, and drank thea [sic] under the shade of some appletrees [sic] ... amidst other discourse, he told me, he was just in the same situation as when formerly, the notion of gravitation came into his mind."[2] And more recently, while relaxing in a California basement, Steve Wozniak realized that a combination of computer circuitry, a typewriter keyboard and video screen was possible (Wozniak, 2006).

Reviewed by Davis et al. (2013), "Many companies, such as Google, provide employees with free time for their own pet projects." However, Armbruster (1989), Elsbach and Hargadon (2006) indicate that "...corporate programs that give employees the opportunity for unstructured free time do not necessarily enhance creativity." With respect to temporal structures, greater encouragement provided by companies for developing free time ideas and incorporating a free, leisure time element into their strategies consist of bootlegging (e.g., Augsdorfer, 2008), brainstorming (e.g., Litchfield, 2009), hacking (Lakhani and Wolf, 2005), and open source invention (Jeppesen and Lakhani, 2010).

This study is structured as follows: in Section 2 we provide a literature review indicating the theoretical and practical need for analysing the working hours dimension with respect to the presence of varieties of imperfections in neo-capital formation processes and related governance failures in agent-based networks. The data and a descriptive analysis are presented in Section 3. Section 4 covers the empirical approach and elaborates on the estimation results. Finally, Section 5 discusses the research implications and future perspectives.

# 2 Theoretical background and literature review

Within the contexts of firms, research labs, universities, or systems of national/regional innovation, scientific and technological innovations are being realized ultimately by the human agent. The evolutionary passage from individual inventors to research and technology development teams as groups of human agents is discussed by Schumpeter with respect to the shift in the institutionalization processes

[1] https://www.math.nyu.edu/~crorres/Archimedes/Crown/Vitruvius.html retrieved on 1 August 2014.
[2] http://www.newtonproject.sussex.ac.uk/view/texts/diplomatic/OTHE00001 retrieved on 1 August 2014.

and structures of the locus of innovation after the World War II.[3]

In this evolutionary and institutional regard, Winter and Nelson (1982) described routines of innovation by big firms in generating technological innovations, and detailed the features of national systems of innovation with comparative analysis (Nelson, 1993). The stock and flow of ideas and interests (in terms of data, information, knowledge, and technology) among people, enterprises and institutions as nodes which are linked to each other by complex set of relationships, financial and discursive ties and interactions, simply forming networks, constituted the idea and the interest that the locus of innovation is embedded in networks and thus, in networking other than solely being dependent on hierarchies and/or markets (Powell, 1990). Granovetter (1973) and Granovetter (1983) developed and discussed the nature of these links, being strong and/or weak ties, for exploitative and explorative activities of the firms, and concluded on the significance of the strength of weak ties for explorative activities in these networks. Turkeli and Wintjes (2014) supersede the special-case systems of innovation (e.g. technological, sectoral, national systems of innovation) by describing the societal system of innovation that concentrates on the interactions amongst these special-case systems of innovation from the perspective of multiplex networks, and stress the importance of these multi-domain and multi-level potentials that are activated by organizing societal synergies between "social participative creativity" and "economic innovative efficiency."

In conjunction to these assessments of systems and networks of innovation, it is indeed relevant to discuss the agent-based extensions to the classical capital approach, namely the neo-capital approaches in terms of human capital, social capital and cultural capital (Lin, 1999). Lin (1999) reviews[4] and describes human capital (accumulation of surplus value by labourers) and social capital (access and use of resources embedded in social networks) as investments. These investments are in technical skills, knowledge, social networks and mutual recognition and acknowledgement at the group level. Capital as investment in the production and circulation of commodities is then of relevance to only the classical capital approach. Other than human and social capital, cultural capital (reproduction of dominant symbols, meanings, and values) is assessed via the internalization or misrecognition of dominant values where solidarity and reproduction of the group form its social capital.

Systems of innovation theories and varieties of neo-capital together provide a fruitful ground to conduct agent-based (e.g. human capital and entrepreneurs) yet aggregate-level analyses (e.g. group networks, regional, and national level analyses). This actor-structure interactive approach enables us

[3]For example, from banker(s)-financed individual inventor(s) (Mark I) to bank- and/or government-funded research teams of big firms (Mark II) - (Schumpeter, 2013).

[4]These neo-capital theories are based on the works of Schultz (1961), Becker (1964), Putnam (1995), Coleman (1988), Burt (2000), Bourdieu (1977), Lin and Smith (1998), Marsden (1988) and Sprengers et al. (1988). Classical theory is of Marx (1909), please refer to Lin (1999) for additional works of these authors.

to analyse the underlying mechanisms of how capital -not necessarily as only classical investments in the production and circulation of commodities, but also as investments in technical skill and knowledge, social networks, mutual recognition, internalization or misrecognition of dominant symbols, meanings, and values- might contribute into our understanding of structuration of innovativeness, and innovation.

At the individual level, similar to the continual construction of human capital, time is a requirement for the re-investment in technical skills and knowledge due to varieties of deterioration in the processes of continual exploitation and exploration of the best and next social capital possibilities and cultural capital schemes. Investment in these social networks, repetitive participatory presence and practices leading potentially to mutual trust, recognition and acknowledgement (which in turn enable further access and use of resources embedded in these social networks) requires time. The internalization or even misrecognition of dominant symbols, meanings, and values via discussions, bargaining, negotiations, self-reflections and decision-making require time as well.

The conditions under which these time requirements might have already been sufficiently incorporated into the official working hours would have necessitated that the source of innovation such as ideas, costs, knowledge as resource, and options were perfectly internal to the firm.[5] However, all of the three neo-capital varieties intrinsically carry imperfections: a continuing need for time in order to participate into continual formation and update of varieties of neo-capital does exist at the individual level. For instance, attending to a professional training programme to achieve a certificate (human capital), attending to a professional networking workshop of industry-university-government organizations in order to learn the conditions of use or access to resources, exchange tacit ideas (social capital), or attending to a visionary public hearing on the policy agenda that covers until 2050 in order to see if a firm recognizes or does not recognize the dominant values, meanings, and/or symbols for innovation (cultural capital). The evidence of the reliance upon external sources, knowledge, and actors with open boundaries in order to develop and commercialize inventions is empirically observed (Arora et al., 2014). In this regard, Arora et al. (2014) states that "this extensive reliance upon outside sources for invention also suggests that understanding the factors that condition the extramural supply of inventions to innovators is crucial to understanding the determinants of the rate and direction of innovative activity." Similarly, other than government or market failures, we can stress the potential of networking imperfections and governance failures (Jessop, 1999) due to these neo-capital related weaknesses and needs of participating agents. The overall reflection of this situation to the average working hours could basically follow two paths: (1) officially working more in terms of time in order to invest in networks and interact with other human, social and cultural groups

[5] A firm that has non-deteriorating human capital with perfect access and use of resources external to the firm embedded in social networks, with an archetypical level of fixed internalization or misrecognition of the dominant values in a static business environment supported via flawless finance and faultless discourse under a techno-economic policy.

due to the boundedness of individual human, social and cultural capital to cope with imperfection and deterioration. This could basically be the inhumane, asocial and uncultured re-formation and update of human, social and cultural capital that could create innovations without a human face. And (2) officially working less in terms of time in order to create either more work-related free time to invest in varieties of neo-capital in an every-day passage to leisure time, or leisure time, whereas even leisure time has its significant contribution to innovativeness (Davis et al., 2013). Therefore, we hypothesize that a trade-off exists between work time and free time with respect to innovative output which we empirically test in Section 4.

# 3 Data and descriptive analysis

Our data are from the statistics published by the Organization for Economic Co-operation and Development (OECD), World Intellectual Property Organization (WIPO), and The World Bank (WB). The period covered is the years 2000 through 2011. Our initial sample consisted of thirty-four OECD countries and Russia. We have imputed a relatively small number of non-consecutive missing values for certain variables. However, due to a large amount of missing data for certain countries, our sample was reduced to twenty-seven countries listed in Table A.1 in the appendix.

The variables used in this study and their definitions are presented in Table 1 and the associated descriptive statistics are in Table 2. There is a large amount of variation in the variable *Patents granted*. As will be discussed in Section 4, this variable enters our model as the dependent variable in per capita terms, and *Hours worked* is our main explanatory variable of interest. We plot these two variables using the z-scores of their averages over time for each country in Figure 1.

At a first glance to Figure 1, we observe that while the distribution of the z-scores of average hours worked is close to normal, the distribution of the z-score of average patents per capita is highly skewed: most countries have below average per capita patent grants (i.e. they are under the horizontal line). This figure also groups the countries into four categories, represented by the four quadrants: those that have higher than average work hours and higher than average patent grants per capita (four countries in quadrant 1), those that are below average in both indicators (thirteen countries in quadrant 3), those that have less than average work hours but have more than average patents per capita (two countries in quadrant 2), and finally the countries that have more than average work hours but still have less than average per capita patent grants (eight countries in quadrant 4).

There are some additional interesting implications of Figure 1. A straightforward expectation would be that countries in which individuals work more on average should produce more innovative output in terms of patents per capita. This would imply that almost all countries would be grouped in quadrants

1 and 3. However, we observe that a large number of countries have more than average work hours but do not have higher than average patent grants per capita. Leaving out a possible outlier, Republic of Korea, we have a visual hint that too much work hours may actually have an adverse effect on innovative output. This observation also implies that the relationship between work hours and innovation may not be linear. That is, rather than a constant returns to work hours on innovation, considering a relationship characterized by diminishing returns could be of interest. We further elaborate on this view and test the relevant hypothesis in Section 4.

We also see in Figure 1 that countries that have less than average patent grants per capita are predominantly located in Europe. Moreover, among these countries, the ones that have higher work hours but less per capita patents are mostly located in Eastern Europe while those that have less than average work hours are in Western Europe.

The variation in the ln total number of granted patents and work hours are presented in Figure 2 which also ranks the countries by these two variables. Republic of Korea ranks high in both total patent grants and work hours, in line with Figure 1. A roughly S-shaped curve resembling a normal distribution is visible for *ln Patents granted*. For *ln Hours*, Republic of Korea and Mexico are at the top of the ranking. This is an interesting observation as in per capita terms, Republic of Korea has the highest patents grants while Mexico is one of the countries with the least patent grants per capita. However, in total terms, Mexico ranks on the top half as sen in the left-hand-side part of Figure 2.

To visualize how innovative output evolved over time, Figure 3 plots the average patents per 1000 people for the above identified four country categories over the period 2000-2011. We observe that in the recent years, the economies what "work less" but have higher per capita patents, have surpassed their peers who "work more" in terms of innovative output.

Table 1: Variable Definitions

| Name | Description |
|---|---|
| *Patents per capita* | Total patent grants count divided by national population. Source: WIPO IP Statistics Data Center. Source for population data: OECD Stat. |
| *Hours Worked* | Average annual hours actually worked per worker. Source: OECD Stat. |
| *GDP* | Gross Domestic Product, constant PPP calculated using constant 2005 USD's. Source: OECD Stat. |
| *Electric cons. per cap.* | Electric power consumption, kilowatt hours per capita. Source: The World Bank. |
| *Tertiary ratio* | Total number of students who are enrolled in tertiary education divided by the national population between the ages 20 and 34. Source: OECD stat (for both education and population data). |
| *R&D to GDP ratio* | Gross domestic expenditure on Research and Development, constant PPP calculated using constant 2005 USD's. Source: OECD Stat |

Table 2: Descriptive Statistics

| **Variable** | **Mean** | **Std. Dev.** | **Min.** | **Max.** |
|---|---|---|---|---|
| Patents granted | 18978.12 | 44664.05 | 16 | 238323 |
| Hours worked | 1778.6 | 218.15 | 1381 | 2512 |
| Hours worked per day (260) | 6.84 | 0.84 | 5.31 | 9.66 |
| GDP (Millions) | 1320921.84 | 2452915.28 | 8398.93 | 13846778 |
| Electric cons. per cap. | 8547.01 | 6992.36 | 1615.31 | 52373.88 |
| Population between 20-34 | 10214399.38 | 13338294.15 | 62867 | 63953140 |
| Population | 47317543.86 | 62964811.46 | 281154 | 311587800 |
| Total tertiary enrollment | 2070669.46 | 3509785.9 | 9667 | 21016126 |
| R&D Expenditure | 29482.66 | 66663.27 | 224.18 | 382536.66 |
| N | | 324 | | |

Figure 1. Countries and their standardized mean work hours and patents per capita.

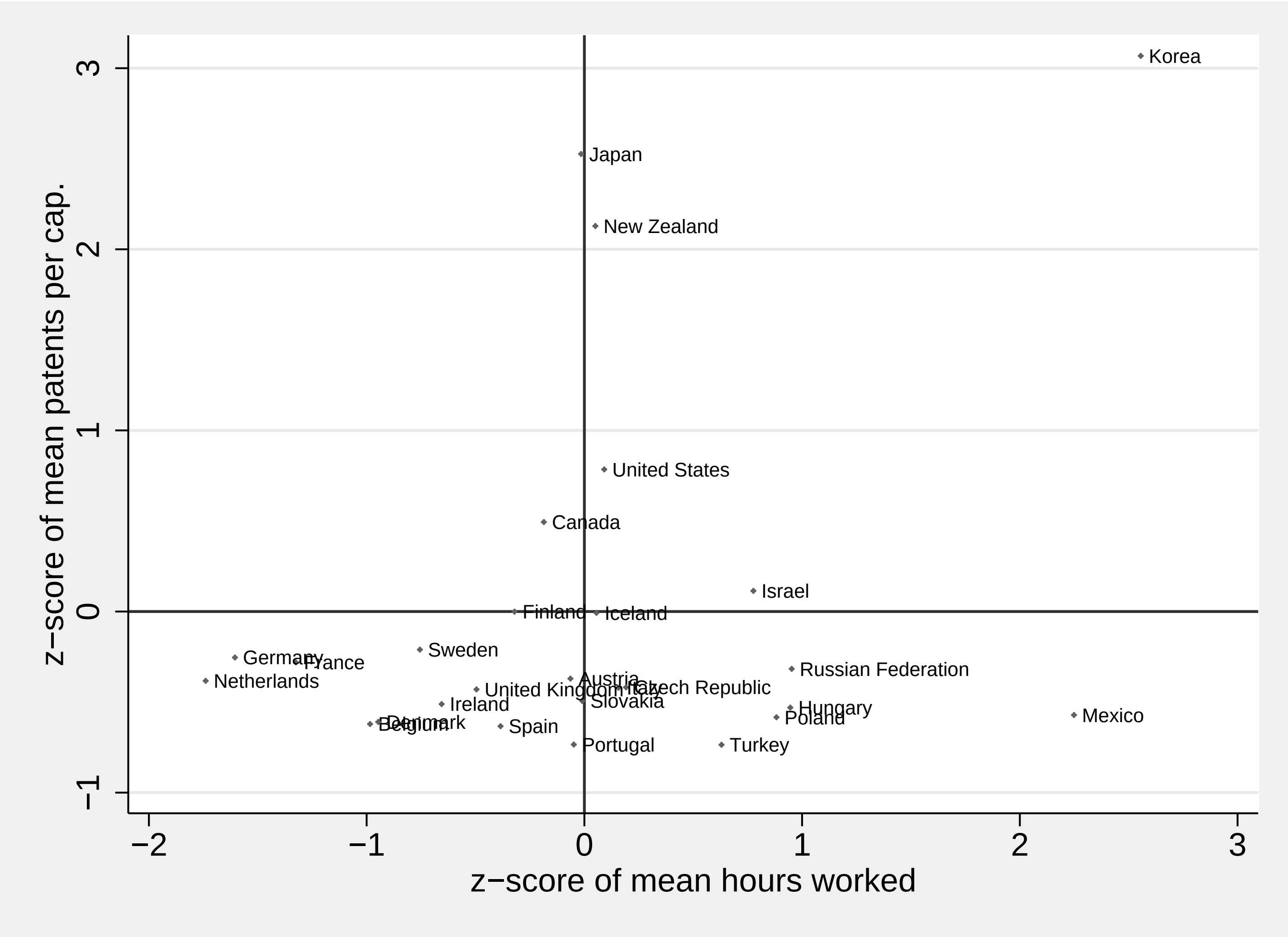
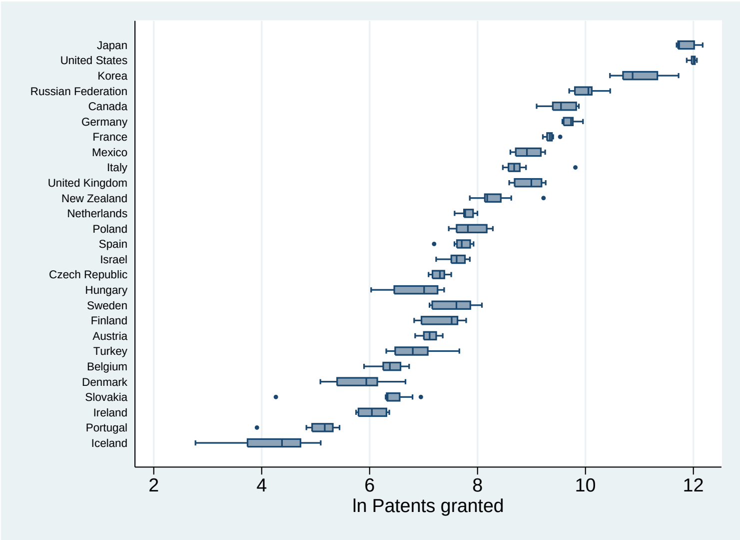


FIGURE 2. Comparison of variation in Patents granted and work hours by country.

(A) ln Patents granted




(B) ln Hours worked

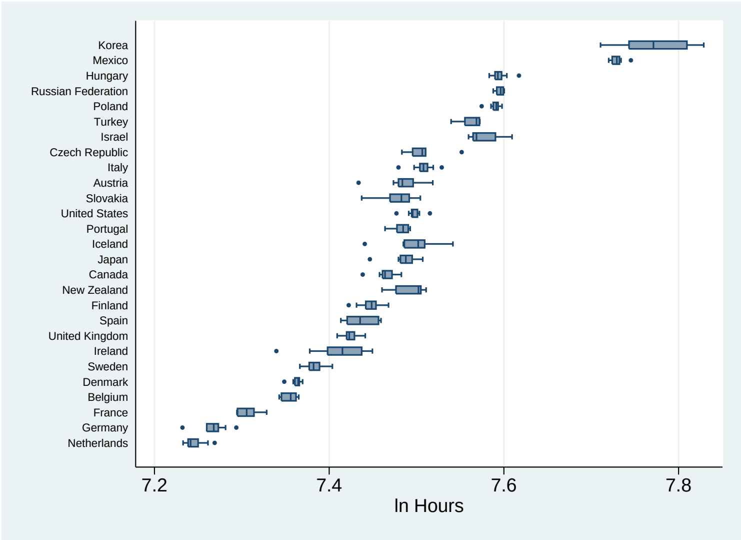
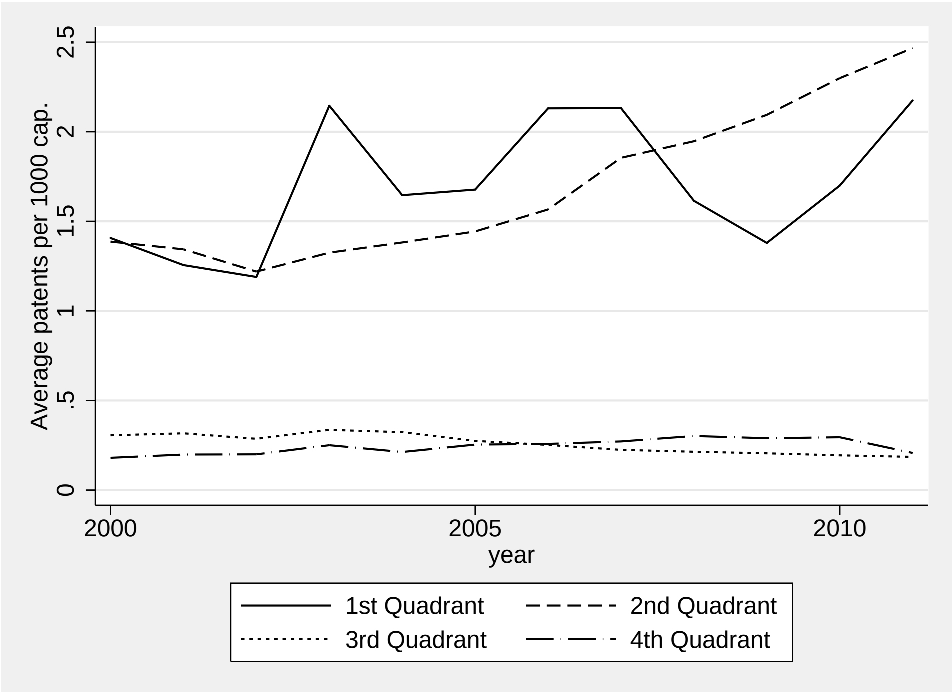



FIGURE 3. Mean work hours and patents per 1000 capita, 2000 to 2011.



# 4 The model and empirical results

We build our empirical specification based on the framework of Jones (1995) where in an economy, the change in knowledge $\dot{A}$ is defined as:

$$\dot{A} = \delta L_A A^{\phi} l^{\lambda - 1} \tag{1}$$

where $L_A$ is the number of people searching for new knowledge and ideas, $A$ is the existing knowledge (or productivity), $l_A$ represents innovation-reducing externalities created by overlaps and duplications in the research and development (R&D) process, and $\delta$ is the "arrival rate" of innovation (i.e. the rate of new idea generation of the R&D process). The parameter $\phi$ represents the external returns on existing knowledge such that if $\phi < 0$ innovation decreases in $A$. In other words, the more the stock of existing knowledge in an economy, the harder it is to produce new knowledge. Alternatively, $\phi > 0$ would mean the opposite (that there are positive external returns to $A$). Finally, in the case where the production of new knowledge is independent of the existing knowledge in an economy, then $\phi = 0$. The parameter $\lambda$ measures the share of duplication externalities such that $0 < \lambda \leq 1$ and $\lambda = 1$ would imply that such externalities do not exist.

In our adaptation of the Jones (1995) model, we argue for the augmentation of innovation oriented labour $L_A$ by individual time spent on labour activity: more work will set the ground for greater creativity which may result in increased innovative output. On the other hand, we argue that this proposed increasing returns on work time is of diminishing nature: after a certain amount of work time, *free time* will take on the role of creativity-enhancing individual time. However, too much of either these two types of time would be undesirable: considering two extremes, a person unemployed for a long-term will be increasingly distanced from markets and will have harder time to assess their needs. Such an individual will also have less access to experience, training, and concentration offered in a work environment. On the other hand, a person that almost has no leisure time, will be mentally and/or physically tired, will not have access to non-work related social engagements which can be creativity-enhancing, and will have less opportunity to think outside the structural limits required by his or her work.

We hypothesize that there exists a balance point between work time and free time which would maximize the creativity required for generating innovative ideas (i.e. a point were the two types of time exchange roles). This motivates us to define the *time-augmented labour* term as $\hat{L}_A$, such that $\hat{L}_A = L_A W^{\alpha}$ where $W$ is the amount of average work time and $0 < \alpha < 1$. After the inclusion of this term, the log-linearized form of 1 is:

$$ln(\dot{A}) = ln(\delta) + ln(\hat{L}_A) + \alpha ln(W) + \phi ln(A) + (\lambda - 1) ln(l) \tag{2}$$

and subtracting $ln(\hat{L}_A)$ from both sides yields:

$$ln\left(\frac{\dot{A}}{L_A}\right) = ln(\delta) + \alpha ln(W) + \phi ln(A) + (\lambda - 1)ln(l) \tag{3}$$

While our empirical specification is based on the theoretical framework of 3, it is not a one-to-one representation of this equation: we represent the diminishing returns proposed by $\alpha$ in the empirical model by representing $\alpha ln(W)$ by a quadratic term as $\beta_1 lnHours + \beta_2(lnHours)^2$ in our empirical model where $Hours$ represents $W$ and is the average work hours per worker as defined in Table 2.

According to Furman et al. (2002), the per capita GDP of a country "captures the ability of a country to translate its knowledge stock into a realized state of economic development" and therefore, "yields an aggregate control for a country‘s technological sophistication." Following this view, we proxy the previous stock of knowledge, $A$, by the level of GDP per capita while the flow of per capita innovation $\dot{A}/L_A$ is measured by the number of patents granted per capita. Even though this measure could be imperfect as not all innovations may be patented and strategic patenting may be present,[6] the number of patents is a commonly used measure in the innovation literature to represent innovative output (Cohen et al., 2000).

It is important to emphasize at this point that our variables are measured as country aggregates. As will be discussed in Section 5, a more specific data set such as industry specific measures may provide certain advantages. However, we argue that positive externalities arising from social interactions are best represented using country aggregate measures. For instance, individuals employed in the aerospace industry may leave work earlier, but if their counterparts in the textile industry are still at work, both groups will be deprived of a potentially creative informal interaction which could perhaps lead to a discussion on a topic such as the materials used in producing pilot or astronaut suits. Therefore, while certain industries may traditionally be more innovative, they may still rely to positive externalities from less innovative sectors to some extent.

In order to control for the possible higher share of patent-seeking individuals involved in the R&D related activities, we control for the relative size of R&D activities in an economy by including the ratio of gross domestic R&D expenditure to GDP. The inclusion of *R&D to GDP ratio* also may help cope with a potential omitted variable bias: if R&D related activities are typically associated with less working time than non-R&D related ones, then patent grants per capita would be high for certain countries not because they have more free time, but because they are engaged in relatively more R&D activities, which in turn allow for more free-time by nature. While this mechanism need not be true in practice, we control for the relative size of the R&D related activities in a country also for the purpose of dealing with this potential issue.

[6]Such as patents that are created by individuals, yet not only owned by individuals but also by firms or organizations, institutions (e.g. university-owned patents, university-invented patents of firms, patents of firms, patents of public research organizations) (Verspagen, 2006; Crespi et al., 2010).

The terms $\delta$ and $l$ are implicitly included in our model. In addition to *R&D to GDP ratio*, we include the ratio of people between the ages twenty and thirty-four who are enrolled in tertiary education, and electricity consumption per capita. *R&D to GDP ratio* and *Tertiary ratio* account for the human capital that can influence the arrival rate $\delta$. On the other hand, as human capital needs to rely on technological capital stock, we aim to measure the arrival rate enhancing non-human capital with *Electric consumption per capita*. Finally, we expect that the negative duplication or overlap externalities defined by Jones (1995) are more likely to be present the larger innovation-oriented activities exist in an economy. Therefore, *R&D to GDP ratio* and *Tertiary ratio* are also expected to account for these externalities.

Finally, as in Furman and Hayes (2004) and Krammer (2009) we allow for a two-year time lag between factors that influence new idea generation and the actual registration of new knowledge such that the dependent variable is measured at time $t+2$. As a result, our empirical specification takes the following form:

$$\begin{aligned} ln(Patents\ per\ capita)_{i,t+2} = {} & \gamma + \beta_1 ln\ Hours_{i,t} + \beta_2\ (ln\ Hours)^2_{i,t} \\ & + \beta_3\ ln\ (GDP\ per\ cap.)_{i,t} + \beta_4\ ln\ (Electric\ cons.\ per\ cap)_{i,t} \\ & + \beta_5\ ln\ (Tertiary\ ratio)_{i,t} + \beta_6\ ln\ (R\&D\ to\ GDP\ ratio)_{i,t} \\ & + e_{i,t} \end{aligned} \tag{4}$$

where $e_{it}$ is the error term. We estimate this model using country specific fixed and random effects estimation together with the inclusion of year dummies.

Our estimation results are presented in Table 3. While both models find the expected signs on the two components of the quadratic term representing work hours, only the in fixed effects (FE) model the quadratic specification is jointly significant with an F-test p-value of 0.0255. A Hausman test of fixed versus random effects yield a p-value of 0.0021, suggesting the use of a fixed effects specification. Therefore, we concentrate on the results suggested by the FE model.

The coefficients on $ln\ Hours$ and $(ln\ Hours)^2$ estimated by the FE model in the first column of Table 3 suggest that in an inverse U-shaped relationship exists between $ln\ Hours$ and $ln(Patents\ per\ capita)_{i,t+2}$ with a maximum at $ln\ Hours \approx 7.45$. For a hypothetical economy which does not have any other holidays other than weekends (i.e. with approximately 260 business days in a year) this value corresponds to about 6.6 hours per day per working persons. Therefore, in such an economy, individuals seeking new ideas would be expected to be more innovative if they work up to 6.6 hours a day. While the innovativeness of these individuals would increase as they work more until this point, their innovativeness is expected to decline if they work further past this estimated maximum work hours. Sufficiently long work hours could even cause individuals to be less innovative compared to amounts of work hours that are below 6.6. This estimated maximum work hours depends on how many work days are in a given year, therefore is increasing in non-work days.

Figure 4 where $ln\ Hours$ and $ln(Patents\ per\ capita)_{i,t+2}$ are plotted visualizes this result. The corresponding value for each country for the given years in the sample are represented with point markers which show the distribution of the data and the country groups. The black curve is the predicted relationship between work hours and patent grants per capita estimated by the FE model, with a maximum at 6.6. The colored lines represent the same relationships estimated by cross-sectional Ordinary Least Squares (OLS) estimations for each year using the same set of explanatory variables.[7,8]

We do not observe significant coefficient estimates on the remaining explanatory variables in our model. Only in the random effects model, *ln Electric consumption per capita* yields a significant coefficient estimate. These non-significance of estimates on the variables that are expected to play an innovation-enhancing role could be due to the previously discussed duplication or overlap externalities which may have offset the expected effects. It could also be that given the profiles of the countries included in our sample,[9] the variation in these variables do not explain the differences in innovative output and only variations in work hours determine these differences.

The correlation matrix of the variables used in the empirical estimation is presented in Table A.2 for exploring possible near-perfect collinearity among the regressors. We do not expect such near-perfect multicollinearity as the strongest observed correlation is about 0.7 and is between *ln Electricity cons. per cap.* and *ln GDP per capita*.

[7]In the yearly cross-sectional estimations, the outlier Republic of Korea is left out.

[8]The OLS predicted curves are smoothed by estimating a fractional polynomial using $ln\ Hours$ and the predicted values of $ln(Patents\ per\ capita)_{i,t+2}$.

[9]Our sample does not include countries that are classified as lower-middle or low income economies as of the completion date of this study according to the World Bank classification at http://data.worldbank.org/about/country-and-lending-groups#Upper_middle_income retrieved on 1 August 2014.

Table 3: Estimation results

| | (1) | (2) |
|---|---|---|
| | FE | RE |
| *ln Hours* | 229.7** | 49.52 |
| | (87.16) | (42.36) |
| $(ln\ Hours)^2$ | -15.41** | -3.113 |
| | (5.748) | (2.786) |
| *ln GDP per capita* | -0.0624 | 0.274 |
| | (0.990) | (0.466) |
| *ln Electric cons. per cap.* | 0.226 | 0.918** |
| | (0.514) | (0.459) |
| *Tertiary ratio* | -4.616 | -2.835 |
| | (2.975) | (2.768) |
| *R&D to GDP ratio* | -35.55 | 16.03 |
| | (32.62) | (20.08) |
| Constant | -864.5** | -215.8 |
| | (324.9) | (161.3) |
| Observations | 270 | 270 |
| Number of countries | 27 | 27 |
| Observations per country | 10 | 10 |
| Year Dummies | Yes | Yes |
| Within R-Squared | 0.127 | |

Table 3: Estimation results (Cont'd)

| | (1) FE | (2) RE |
|---|---|---|
| Hours of work (260 days) | 6.631 | 10.96 |
| F-test p-value for quadratic variable | 0.0255 | 0.154 |
| Hausman test FE vs RE p-value | 0.0021 | |

Standard errors in parentheses: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

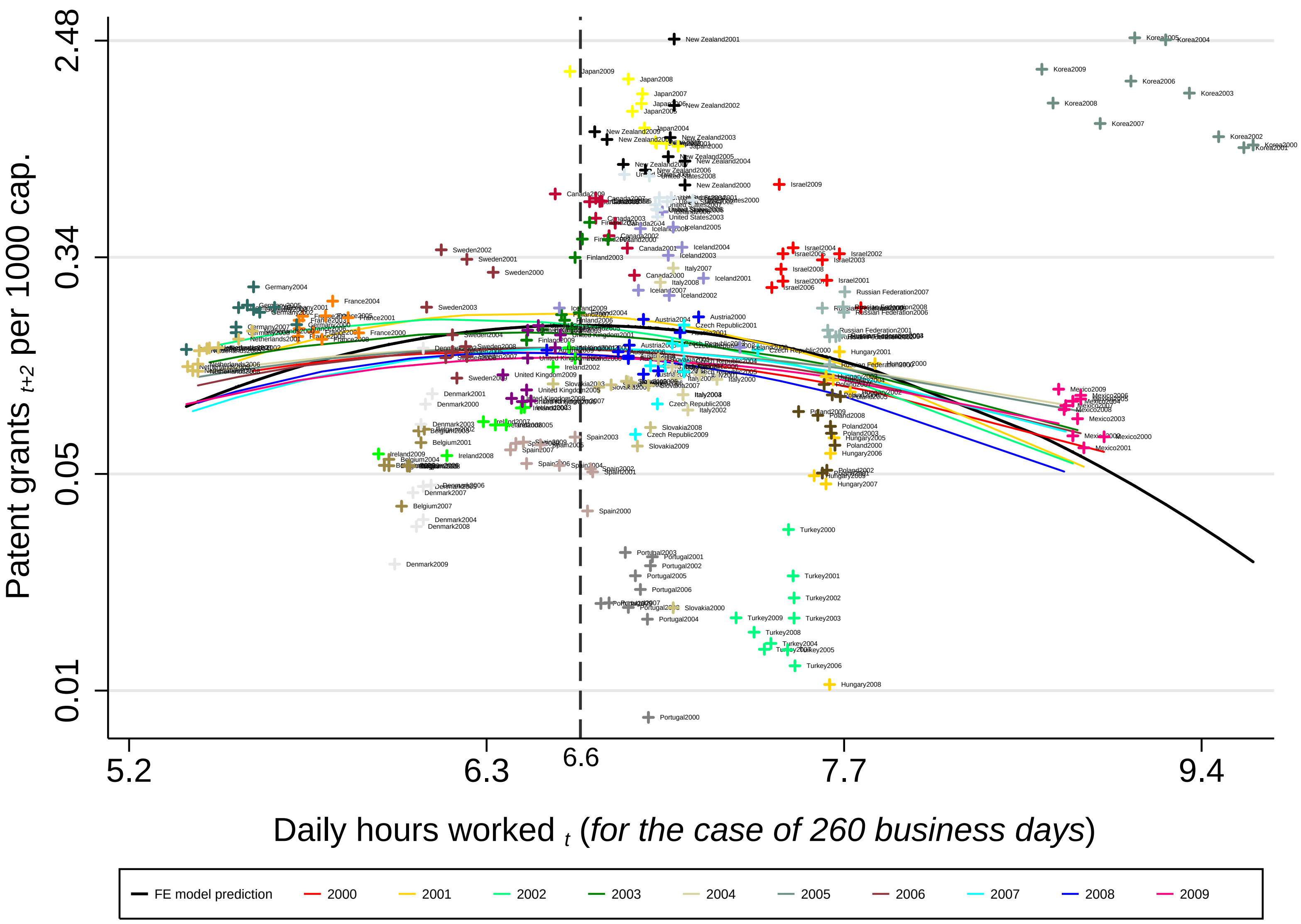



FIGURE 4. Estimated relationship between work hours and patent grants, FE model.

## 5 Concluding remarks

This study has suggested the inclusion of individual work time in the knowledge production function such that labour is represented in a time-augmented manner. Additionally, we have hypothesized that work time yields diminishing returns for innovation. We observe that after a maximum point, free time, as opposed to work time, assumes the innovation enhancing role. Based on a sample consisting of only upper-middle and upper income economies, we estimated that if an economy has about 260 business days, this estimated maximum corresponds to about 6.6 work hours per day.

Our research tested the hypothesis under question in aggregate terms. Innovation ultimately happens in an individual's brain, and factors such as creativity, motivation, tiredness, and interactions with other individuals are closely related to individual time. We advocate that future research is needed in order to further explore the relationship between time and innovation which we have uncovered in this study. Research using industry level data, urban level spatial units, and firm level survey data together with country-specific case studies could shed more light on how the work time - free time balance can be thought of in relation to achieve higher innovativeness.

Finally, our descriptive analysis suggested a categorization method of economies based on their innovative outputs and work hours. This categorization could be of interest for future case studies as it can form a basis for country-comparative research framework.

# A Appendix

Table A.1: List of countries

| |
|---|
| Austria |
| Belgium |
| Canada |
| Czech Republic |
| Denmark |
| Finland |
| France |
| Germany |
| Hungary |
| Iceland |
| Ireland |
| Israel |
| Italy |
| Japan |
| Korea |
| Mexico |
| Netherlands |
| New Zealand |
| Poland |
| Portugal |
| Russia |
| Slovakia |
| Spain |
| Sweden |
| Turkey |
| United Kingdom |
| United States |

Table A.2: Cross-correlation table

| Variables | *ln Hours* | *ln GDP per capita* | *ln Electricity cons. per cap.* | *Teritary ratio* | *R&D to GDP ratio* |
|---|---|---|---|---|---|
| *ln Hours* | 1.000 | | | | |
| *ln GDP per capita* | -0.632 | 1.000 | | | |
| *ln Electricity cons. per cap.* | -0.345 | 0.709 | 1.000 | | |
| *Tertiary ratio* | -0.009 | 0.321 | 0.573 | 1.000 | |
| *R&D to GDP ratio* | -0.237 | 0.598 | 0.654 | 0.440 | 1.000 |

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